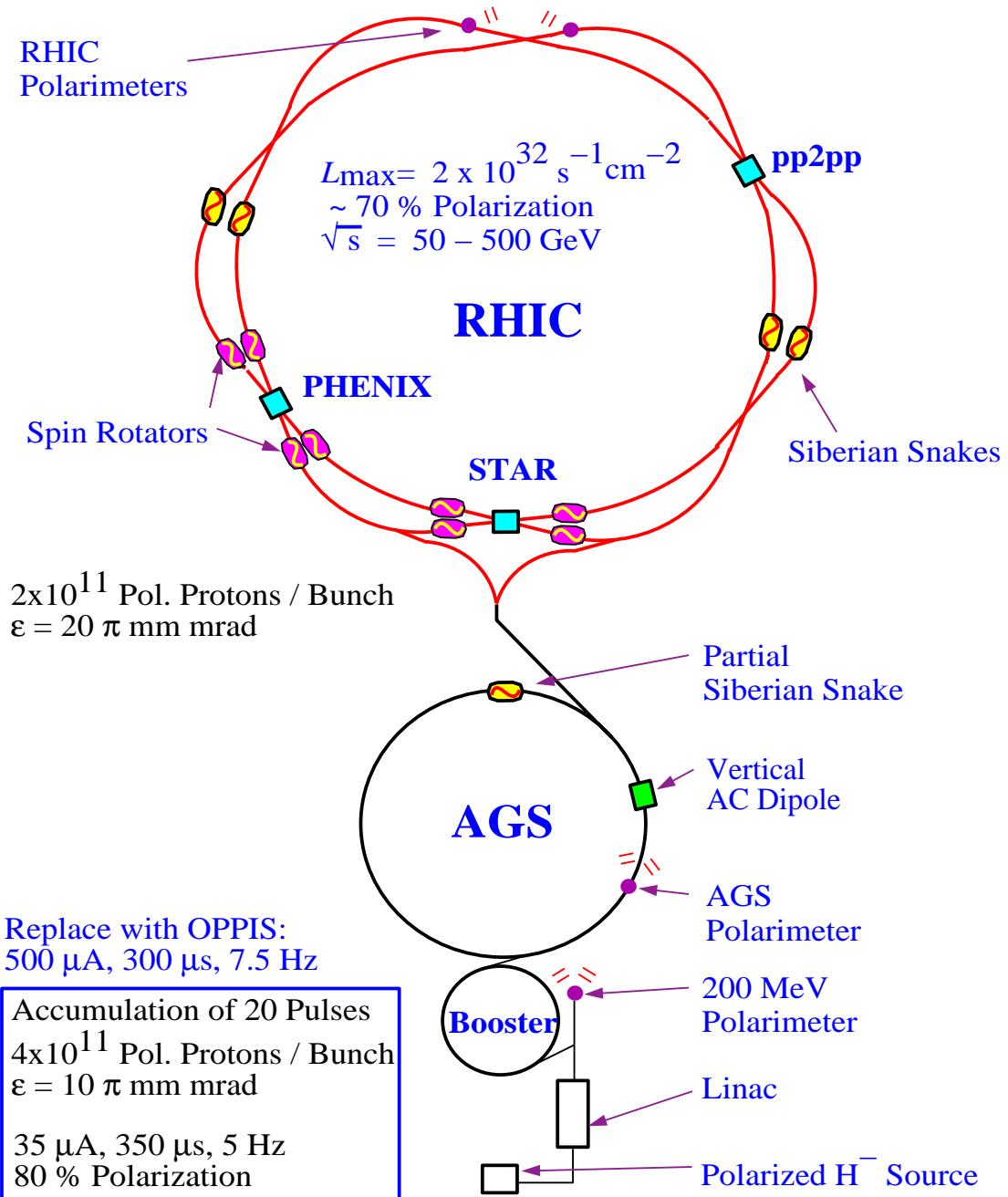
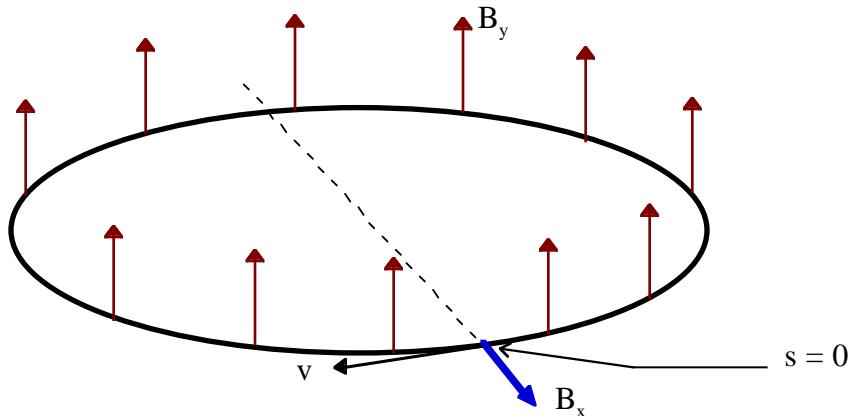


## Polarized Proton Collisions at BNL



## Crossing Imperfection Resonances...

Single horizontal field error producing a spin rotation about the x-axis of amount  $\Delta\phi = 2\pi\varepsilon = G\gamma B_x L/(B\rho) \dots$



Once around the accelerator, the spin is governed by

$$\begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix}_{n+1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos 2\pi\varepsilon & -\sin 2\pi\varepsilon \\ 0 & \sin 2\pi\varepsilon & \cos 2\pi\varepsilon \end{pmatrix} \begin{pmatrix} \cos 2\pi G\gamma & 0 & \sin 2\pi G\gamma \\ 0 & 1 & 0 \\ -\sin 2\pi G\gamma & 0 & \cos 2\pi G\gamma \end{pmatrix} \begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix}_n$$

$$= \begin{pmatrix} \cos 2\pi G\gamma & 0 & \sin 2\pi G\gamma \\ \sin 2\pi\varepsilon \cos 2\pi G\gamma & \cos 2\pi\varepsilon & -\sin 2\pi\varepsilon \cos 2\pi G\gamma \\ -\cos 2\pi\varepsilon \sin 2\pi G\gamma & \sin 2\pi\varepsilon & \cos 2\pi\varepsilon \cos 2\pi G\gamma \end{pmatrix} \begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix}_n$$

Spin rotation axis  
(stable spin direction):

If  $\varepsilon = 0$ ,  $\mathbf{n} = (0, \pm 1, 0)$   
If  $G\gamma = \text{intgr}$ ,  $\mathbf{n} = (\pm 1, 0, 0)$ .

$$n_x = -\frac{\sin \pi\varepsilon \cos \pi G\gamma}{\sqrt{\sin^2 \pi\varepsilon + \cos^2 \pi\varepsilon \sin^2 \pi G\gamma}},$$

$$n_y = -\frac{\cos \pi\varepsilon \sin \pi G\gamma}{\sqrt{\sin^2 \pi\varepsilon + \cos^2 \pi\varepsilon \sin^2 \pi G\gamma}},$$

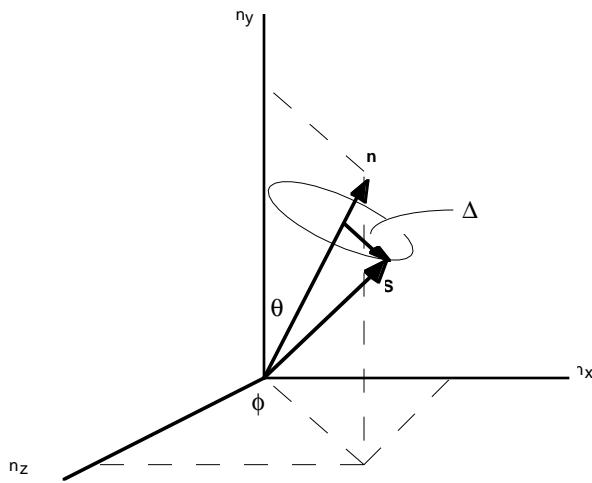
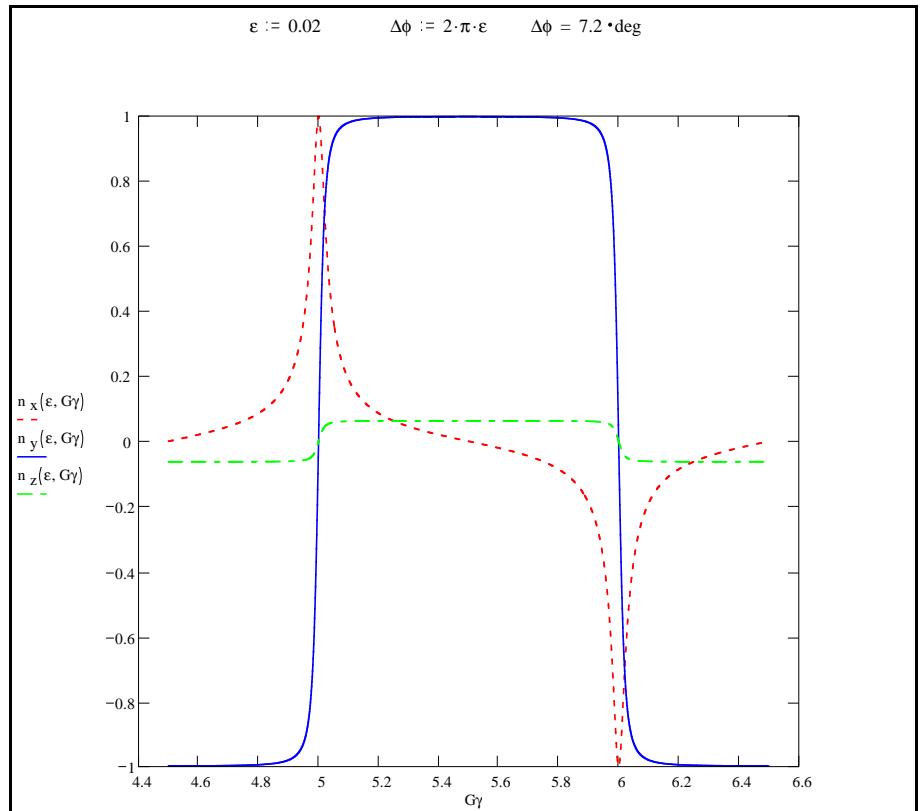
$$n_z = -\frac{\sin \pi\varepsilon \sin \pi G\gamma}{\sqrt{\sin^2 \pi\varepsilon + \cos^2 \pi\varepsilon \sin^2 \pi G\gamma}}.$$

Resulting precession angle,  $2\pi\nu_s$ , ( $\nu_s$ = “spin tune”) given by:

$$\cos \pi\nu_s = \cos \pi\varepsilon \cos \pi G\gamma$$

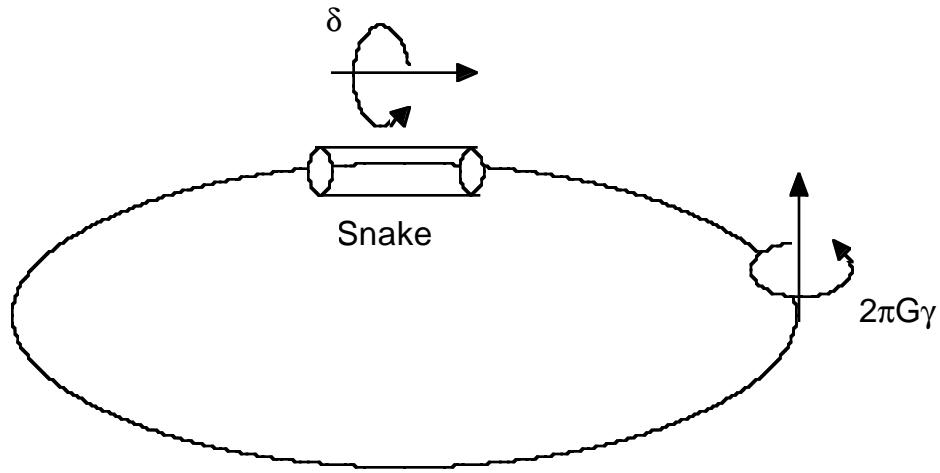
Stable spin vector changes direction as  $G\gamma$  passes through integral values

If slowly (adiabatically) cross these resonance conditions particle spin precession can follow along (spin flip)



Adiabatic if:  $\Delta(G\gamma) \text{ per turn} \ll \epsilon^2$

## Siberian Snakes and Partial Siberian Snakes...



Intentionally introduce a strong horizontal field to produce large spin rotation --

$$\begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix}_{n+1} = \begin{pmatrix} \cos\delta & \sin\delta & 0 \\ -\sin\delta & \cos\delta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos 2\pi G\gamma & 0 & \sin 2\pi G\gamma \\ 0 & 1 & 0 \\ -\sin 2\pi G\gamma & 0 & \cos 2\pi G\gamma \end{pmatrix} \begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix}_n = M \begin{pmatrix} S_x \\ S_y \\ S_z \end{pmatrix}_n$$

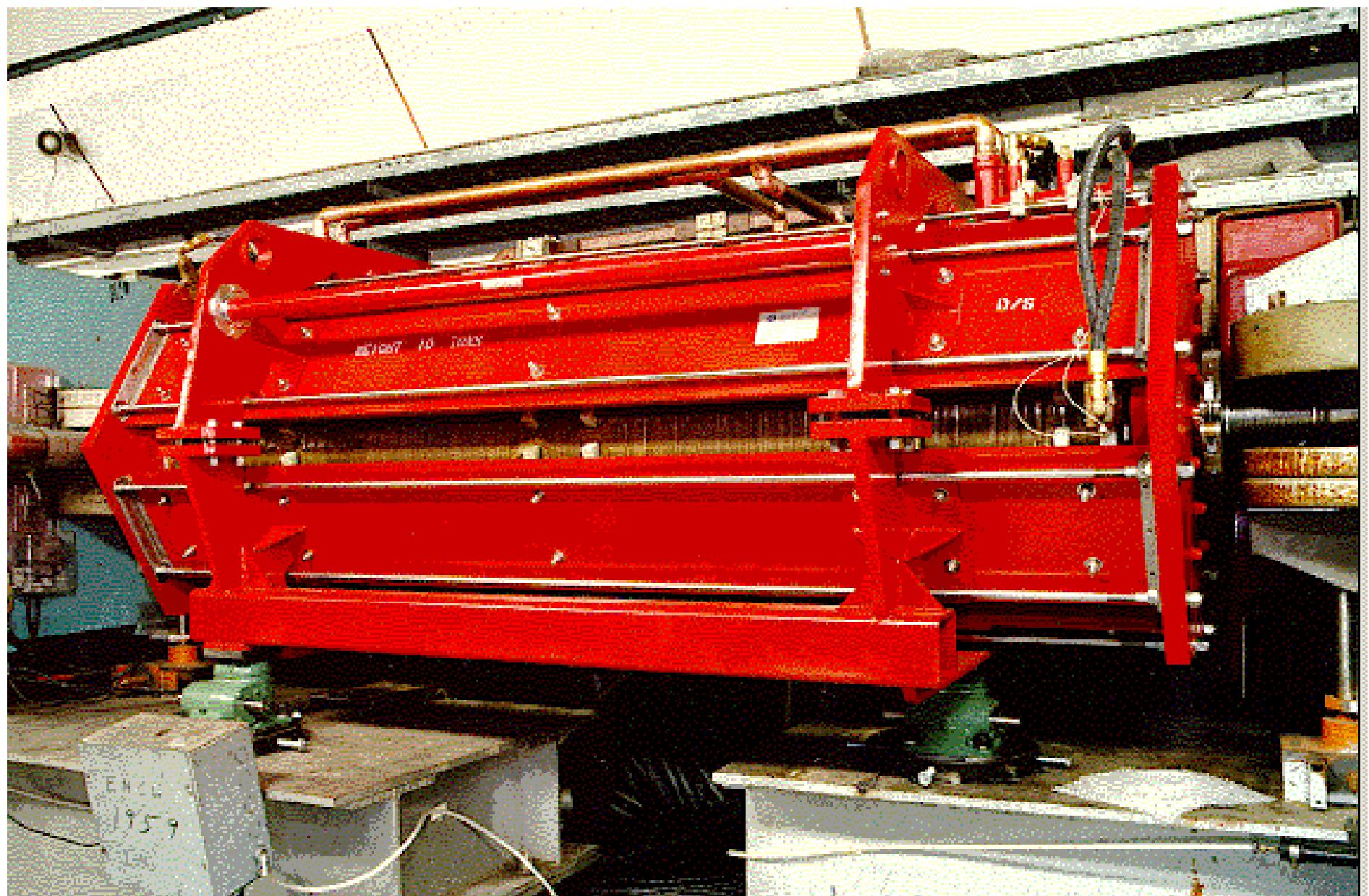
$$\cos\pi v_s = \cos(\delta/2) \cos\pi G\gamma$$

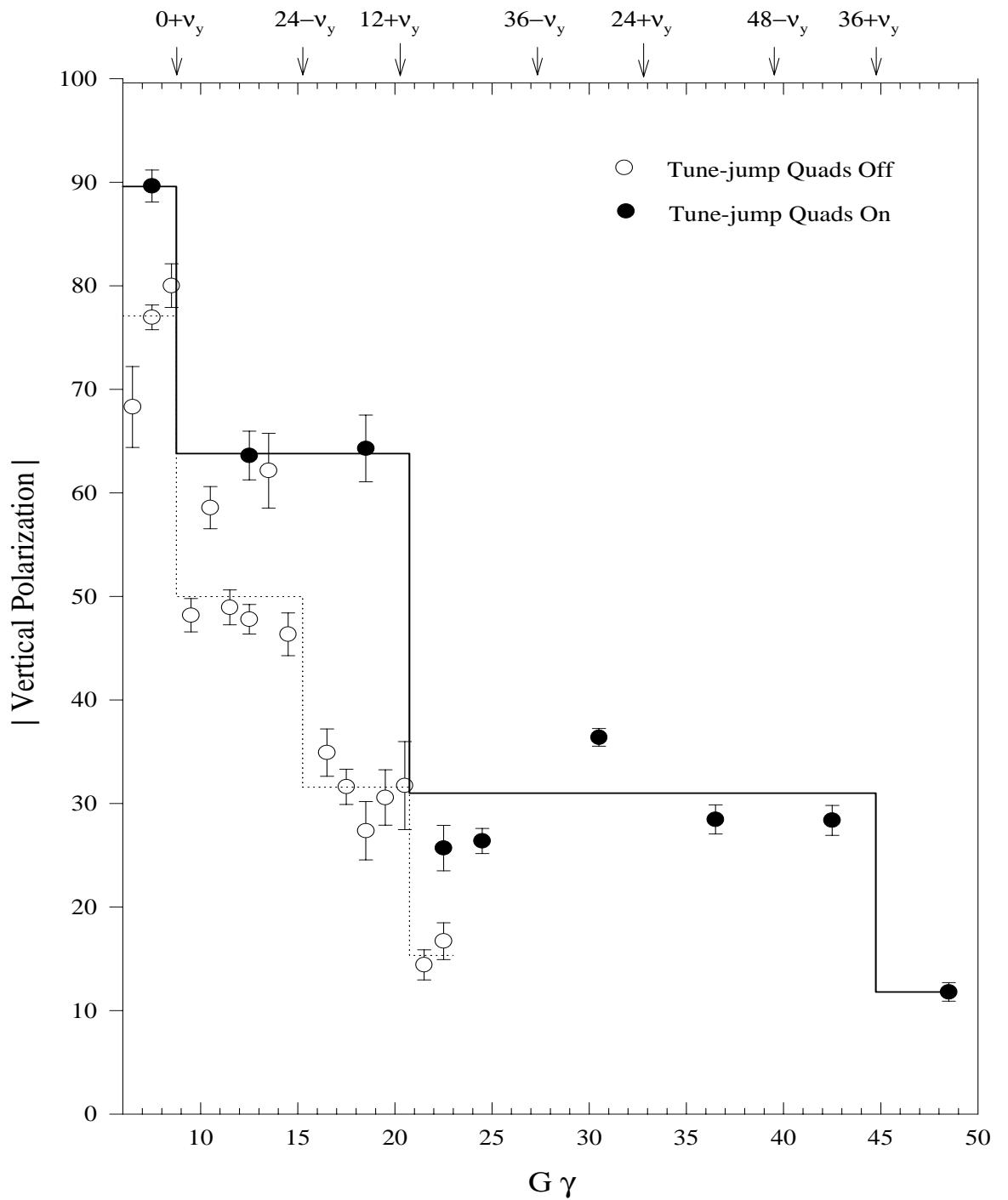
So, if  $\delta = \pi$  (Full Siberian Snake), then  $v_s = 1/2$ ,

if  $\delta = 0$  (No Snake!), then  $v_s = G\gamma$ ,

and otherwise (Partial Snake) , then

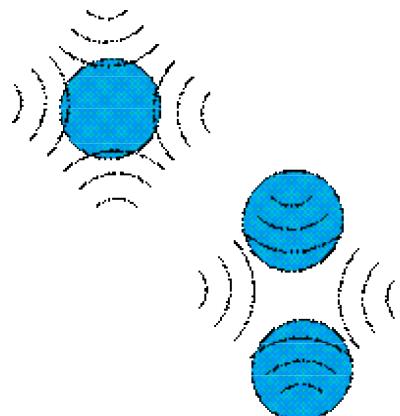
$v_s$  cannot be an integer!



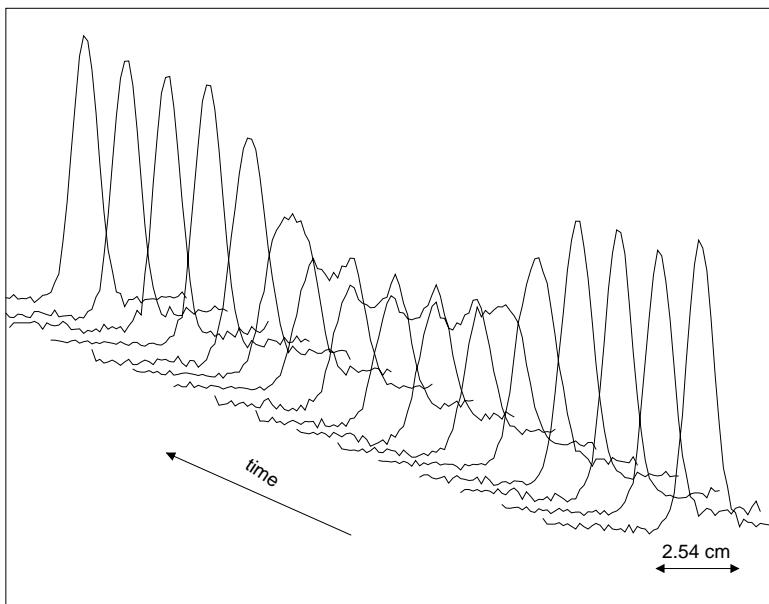
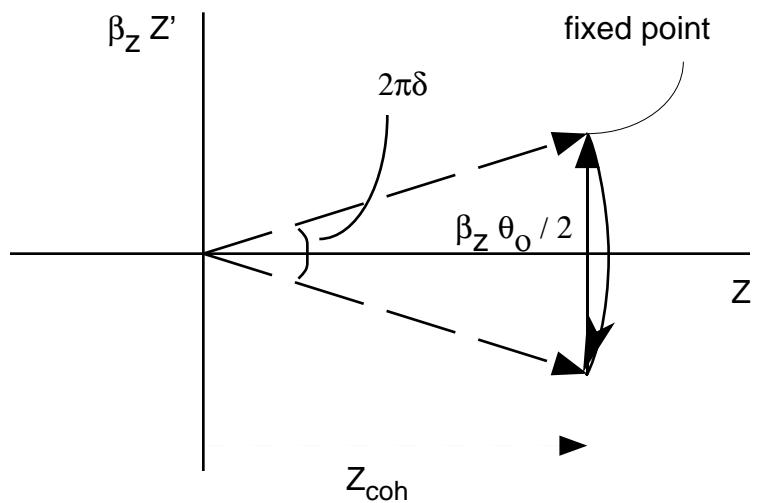


# Crossing Intrinsic Resonance using RF Dipole

Adiabatically generate a Coherent Betatron Oscillation to increase the resonance strength seen by every particle; thus, all will flip spin



In frame rotating at  
the RF dipole frequency:

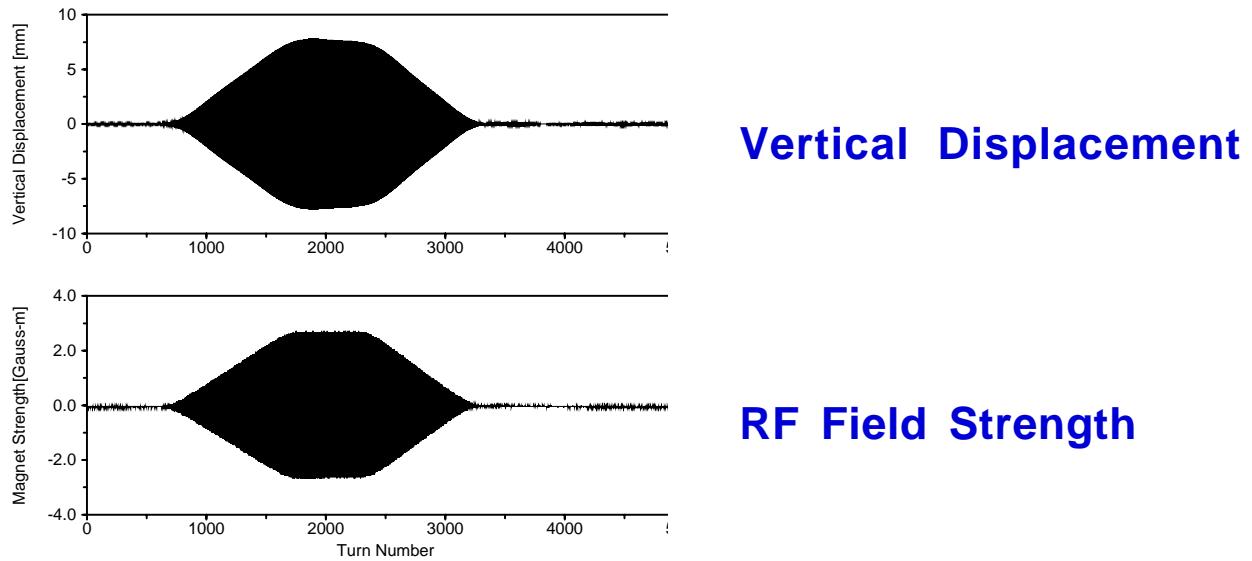


$$Z_{coh} = \beta_z \theta_0 / 4\pi\delta$$

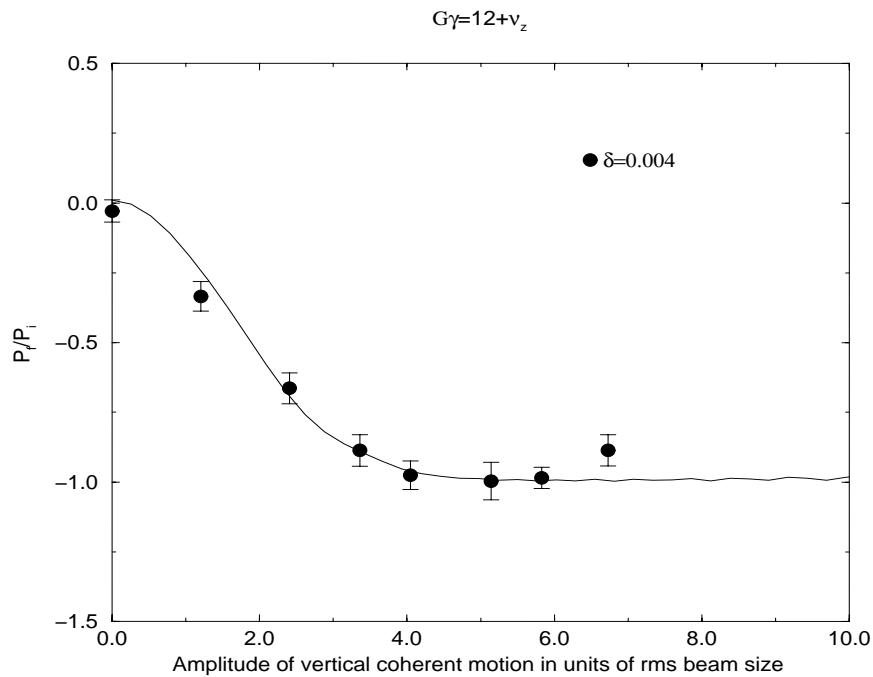
$$\delta = v_{rf} - v_\beta$$

Emittance is preserved  
throughout the process

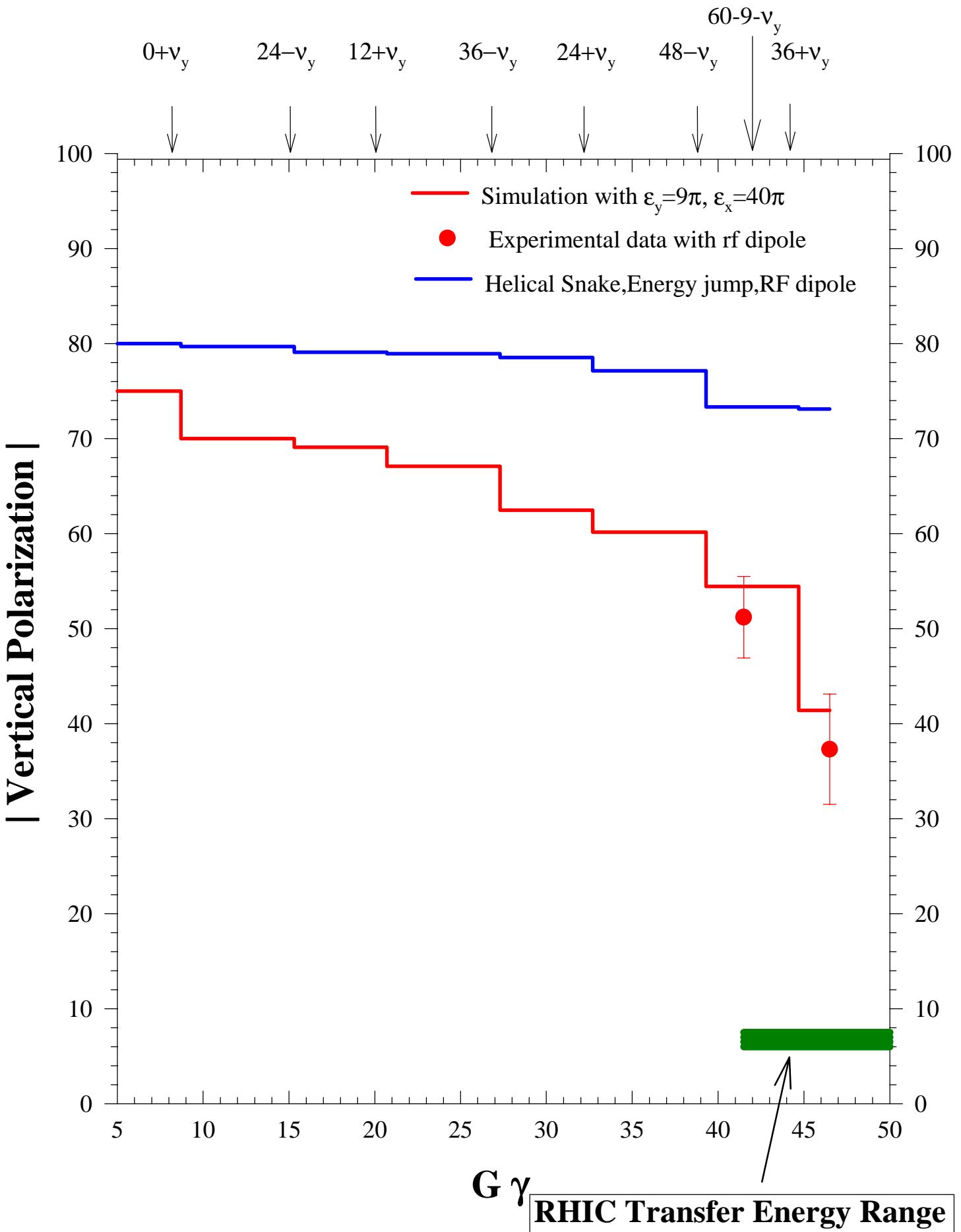
## Crossing intrinsic resonance using RF dipole magnet...



**Total Spin Flip is generated...**



**The RF dipole modulation tune was separated  
from the betatron tune by 0.004**



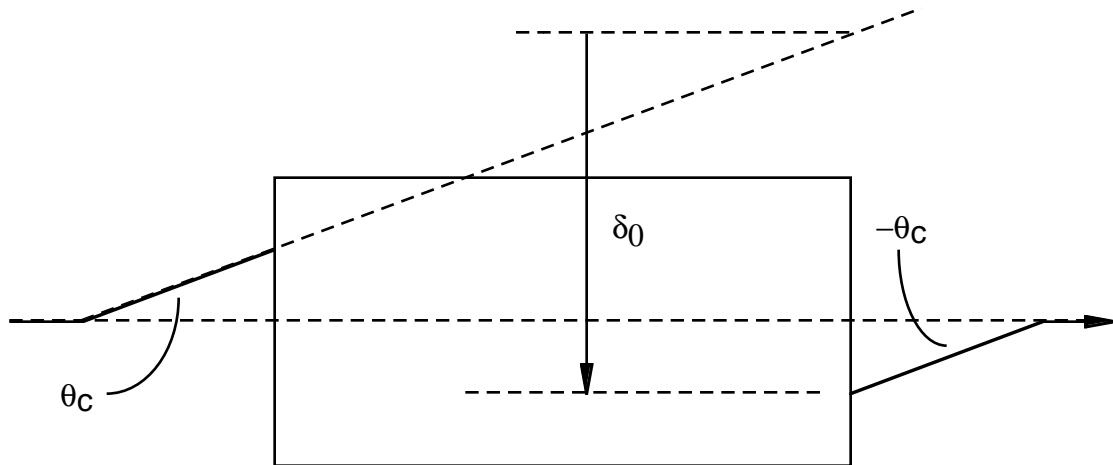
## **AGS Status:**

- Recent polarized proton runs, using AC Dipole
  - \* Successfully crossed strong intrinsic resonances using AC dipole to generate sustained coherent betatron oscillations
  - \* Record polarization (50%) at high energy in AGS
  - \* Improvement to 70% needed, and plans exist
    - ⇒ Improvements to orbit/feed-down effects, emittance
    - ⇒ Improvements to coupling
- Main issue will be control of both horizontal and vertical emittances in the AGS
- New optically pumped polarized ion source ([OPPIS](#)) in collaboration with KEK, RIKEN, and TRIUMF; presently being assembled at TRIUMF for testing; scheduled to arrive at BNL 1999; designed to reach intensity goals of RHIC
- Improve transverse coupling in AGS using

◆ **Helical Partial Siberian Snake**

## Helical Partial Siberian Snake for the AGS

- Use two dipole magnets and a helical dipole magnet



$$\delta_0 = \frac{B_0 L^2}{2\pi(B\rho)}$$

$\theta_c = 15$  mrad

$B_0 = 1.5$  Tesla,  $L = 1.5$  m;  $\delta y_{max} = 25$  mm

(at injection)

Spin Rotation axis: mostly longitudinal, 5% rotation

- \* Transverse coupling from helical dipole
  - = 6% of transverse coupling from solenoid
  - (at first resonance; even better at higher energies)